LASER TUNING BY SPECTRALLY DEPENDENT SPATIAL FILTERING

Field of the Invention

This invention relates to tunable lasers, and also provides a novel laser tuning mechanism.

5   ## Background of the Invention

A) Background: Lasers

A laser consists of a pumped gain medium placed within an optical resonator. The pumped gain medium provides light amplification, and the optical resonator provides optical feedback, such that light can circulate within the optical resonator and
10   be amplified by the gain element repeatedly. The gain medium can be pumped in various ways to provide optical amplification, including but not limited to electrical pumping and optical pumping. If the round trip loss within the optical resonator is less than the round trip gain provided by the gain element, the optical power increases on each round trip around the cavity. Since the amplification provided by the gain
15   element decreases as the circulating optical power increases (an effect referred to as gain saturation), the steady state circulating power is the power required to make the round trip gain equal to the round trip loss. One of the elements within the optical resonator acts as the output coupler, where a certain fraction of the circulating power is emitted from the optical resonator, and constitutes the useful laser output. A partially
20   transmitting mirror is a typical output coupler. It is frequently useful, for laser control, to provide one or more secondary output couplers in the optical resonator, where a small fraction of the circulating optical power is emitted from the secondary output coupler(s) in such a way as to be easily separated from the useful laser output.

An especially relevant laser for the present invention is an external cavity
25   semiconductor laser. In such a laser, the gain medium is typically an electrically pumped single-mode optical waveguide. This waveguide has finite length, so it is

terminated by two endfaces. Any semiconductor laser where the defining mirrors of the optical resonator are not the two endfaces of the gain medium waveguide is called an external cavity semiconductor laser, since in the course of a round trip, light leaves the gain element waveguide and reenters it. An optical beam emitted from an endface

5   of a single-mode optical waveguide always has a characteristic amplitude and phase profile, referred to as the mode profile. This beam then propagates through the external cavity elements (i.e. everything except the gain element, usually), and returns to the gain element waveguide. It is convenient to define the "external cavity" as comprising all optical elements the beam encounters from the time it leaves the gain

10   element waveguide to the time it returns to impinge on the waveguide endface. Frequently, the external cavity consists of a sequence of transmissive optical elements terminated by a mirror, called the return mirror, which retroreflects the optical beam back through the sequence of transmissive optical elements to impinge on the endface of the gain medium waveguide. The amplitude and phase profile of the return beam is

15   generally not exactly the same as the mode profile, and in such cases, not all of the return beam power is launched (i.e. coupled) into the gain element waveguide. For example, if a certain power P_b impinges on the waveguide endface, only some lesser amount of power P_0 is launched into the waveguide. The coupling efficiency $\eta = P_0/P_b$ depends on how close the return beam amplitude and phase profile is to the mode

20   profile. We refer to loss due to launch inefficiency as mode mismatching loss.

The emission wavelength of the laser is determined by the wavelength dependence of the round trip loss and the round trip gain. If the gain medium provides amplification over a wide wavelength range, and is homogeneously broadened, then the emission wavelength of the laser will be largely determined by the wavelength at

25   which the round trip loss in the resonator is minimized. A gain medium is homogeneneously broadened if gain saturation reduces the optical gain at all wavelengths, and is inhomogeneously broadened if gain saturation only reduces the optical gain at or near the wavelength of the saturating optical beam. Thus, the most

common way to make a tunable laser is to insert optical element(s) within the cavity to create a tunable intracavity bandpass filter. Since a bandpass filter has low loss for a narrow range of optical wavelengths centered about some center wavelength λ_c, and high loss for wavelengths outside this range, such a filter will tune the laser emission

5   wavelength.

B) Background: Acousto-optic devices

While many kinds of devices have been used as tuning elements within lasers, the use of acousto-optic (AO) devices as laser tuning elements is most relevant for the present invention. Acousto-optic devices are described in textbooks such as J. Xu and

10   R. Stroud, Acousto-Optic Devices: Principles, Design and Applications, Wiley, New York, 1992. For our purposes it is sufficient to define an AO device as any device where the AO interaction is manifested. The AO interaction is a parametric three wave mixing process where an incident optical beam and an acoustic wave interact to generate a second optical wave, with an efficiency that primarily depends on the

15   incident optical wavelength and the acoustic frequency. We refer to the second optical wave that is generated as the first order beam, or diffracted beam; and we refer to that portion of the incident beam that is not converted to the first order beam and exits the device as the zeroth order beam, or undiffracted beam. The zeroth and first order beams may always be distinguished, since the optical frequency of the zeroth order

20   beam is the same as the incident optical frequency, while the optical frequency of the first order beam is larger or smaller than the incident optical frequency by an amount equal to the acoustic frequency. We refer to this effect as the "frequency shift" of the first order beam. The zeroth and first order beams may also differ in other ways, such as propagating in different directions, or having different states of polarization. The

25   acoustic wave in an AO device is typically generated by a transducer bonded to a surface of the AO device, where applied electrical power at a suitable RF frequency acts to launch an acoustic wave of the same frequency into the AO device.

Since the AO interaction is a parametric three wave mixing process, the incident optical beam is efficiently converted to the diffracted beam only for a narrow range of incident optical wavelengths, centered about some center wavelength λ_c at which the phase matching condition is met. The center wavelength λ_c of the AO

5   interaction can be changed by changing the RF frequency applied to the AO device. Therefore, if we regard an AO device as an optical three port device, with one input and two outputs (zeroth order and first order), then transmission from input to first order output (first order transmission) gives a tunable bandpass filter, and transmission from input to zeroth order output (zeroth order transmission) gives the corresponding

10   tunable notch filter (i.e. high loss for a narrow range of optical wavelengths centered about some center wavelength λ_c, and low loss for wavelengths outside this range). Although many different AO devices are shown in the literature, such as AO tunable filters (AOTF), AO deflectors and AO modulators, this general description (i.e. bandpass filter in first order transmission and notch filter in zeroth order transmission)

15   is applicable to all AO devices.

C) Background: Acousto-optic laser tuning elements

A preferred embodiment of the present invention entails the use of an AOTF in zeroth order transmission to tune an external cavity semiconductor laser. We refer to the resulting laser as a "zeroth order AOTF laser". The novelty and nonobvious nature

20   of the zeroth order AOTF laser is best appreciated by briefly reviewing the use of AO devices to tune lasers.

Acousto-optic devices were first used to tune dye lasers [e.g. as described in Streifer et al., Applied Physics Letters 17(8) p335 1970; Taylor et al., Applied Physics Letters 19(8) p269 1971; Hutcheson et al., IEEE Journal of Quantum Electronics, p

25   462 Apr 1974]. Subsequently, AO devices were used to tune other lasers where the gain medium has a broad bandwidth, such as fiber lasers [US 5,189,676 Wysocki et al; US 5,255,274 Wysocki et al; US 5,812,567 Jeon et al], semiconductor lasers [Coquin

et al., Electronics Letters 24(10) p599 1988; Koh et al., Proc. SPIE v3631 p98 1999;

Zorabedian, IEEE Journal of Lightwave Technology 13(1) p62 1995], and titanium-

doped sapphire lasers [US 5,835,512 Wada et al 1998]. In addition, there are several

reports in the patent literature where general methods of tuning a laser with an AO

5   device are disclosed, such as [US 4,118,675 Rahn et al 1978] where the AO device

acts as a beam deflector and dispersive element simultaneously to force oscillation at a

desired wavelength. GB 2,153,137 Hall et al. 1985, discloses the use of an AO beam

deflector and separate dispersive element to tune a laser. In US 5,724,373, Chang

1998, discloses a method for AO laser tuning where the AO interaction provides a

10   waveguide mode conversion device, and narrowband filtering is obtained by use of this

AO device in combination with appropriate polarization optics within the laser cavity.

In all of the references cited above, the AO device functions as a bandpass filter

within the laser cavity, either independently, such as in the cases where the device is an

AO device operating in first order transmission, or in combination with one or more

15   intracavity optical elements, such as the combination of an AO mode converter with

polarizers, or the combination of an AO beam deflector with the cavity round trip

consistency condition to provide frequency selective feedback. In all the above cited

references the diffracted (i.e. first order, deflected or mode converted) beam is of

primary importance for the tuning mechanism, and the undiffracted (i.e. zeroth order,

20   undeflected or non-mode converted) beam is not utilized by the tuning mechanism.

All of these references teach the use of an AO device in first order transmission to tune

a laser, and none teach a the use of an AO device in zeroth order transmission to tune

a laser. Since first order transmission through an AO device entails a frequency shift,

much of the prior art cited above is concerned with the effect of the uncompensated

25   frequency shift on laser operation, and/or on various methods of compensating for the

frequency shift so as to eliminate its effect on laser operation.

One reference teaches the use of other than the first order beam (although not

the zeroth order beam) in an AO interaction to tune a laser. US 5,384,799 to Osterwalder (1995) discloses the formation of a periodic refractive index perturbation within an AO device due to a standing acoustic wave. Osterwalder further discloses a tunable narrowband feedback mechanism into the laser cavity, based on the

5   narrowband reflection created by the disclosed periodic refractive index perturbation. A zeroth order AOTF laser is not taught by Osterwalder.

A fundamental difference between a zeroth order AOTF laser and the laser of Osterwalder is that Osterwalder teaches the presence of a narrowband back reflection from an acousto-optic device. No such back reflection is observed from an AO device

10   in zeroth order transmission in experiments designed specifically to manifest this effect. Furthermore, coupled mode theory, a recognized theoretical approach for analyzing acousto-optic interactions that is well known to those skilled in the art, categorically predicts no narrowband back reflection from an AO device in zeroth order transmission.

15   There are additional significant differences between the teachings of Osterwalder and the zeroth order AOTF laser. Osterwalder teaches the use of a standing acoustic wave to create the disclosed refractive index perturbation. In contrast, an AO device in zeroth order transmission is driven by a traveling acoustic wave. Osterwalder teaches the importance of a collinear alignment of optical and

20   acoustic wave vectors. In contrast, an AO device in zeroth order transmission can be based on a non-collinear phase matching geometry (e.g. as disclosed in US Patent 5,329,397). Osterwalder discloses a configuration with a waveguide AO device. In contrast, an AO device in zeroth order transmission is not a waveguide device.

In fact, the zeroth order AOTF laser is a preferred embodiment of a novel,

25   nonobvious, and more general laser tuning mechanism we have discovered, which is referred to herein as "spectrally dependent spatial filtering" (SDSF). Various specific embodiments of the SDSF mechanism, using different gain media and/or different

tuning elements, may be preferable in certain applications. Possible gain media include, but are not limited to, Erbium-doped optical fiber and electrically pumped semiconductor gain media. Possible tuning elements include, but are not limited to, volume hologram devices, and non-AO three wave parametric interaction devices,

5   such as electro-optic devices. Note that the AO interaction is one example of a three wave parametric interaction. Suitable control inputs for volume holograms and/or three wave parametric devices include electrical frequencies and/or voltages.

In general, tunable diffractive optical elements operating in "zeroth order" (i.e. based on the use of the undiffracted beam) are regarded as suitable tuning elements for

10   the SDSF mechanism, and are referred to as SDSF tuning elements. In transmission through an SDSF tuning element, the total power in the optical beam may decrease, due to attenuation within the tuning element, and the amplitude and/or phase profile of the beam may be changed, which is herein referred to as "distortion". This distortion and attenuation will depend on the transmitted wavelength. Note that an SDSF tuning

15   element as defined here is not obviously a suitable tuning element for a laser, since an SDSF tuning element typically acts as a notch filter in isolation, and laser tuning requires a bandpass filter.

Summary of the Invention

The name given to our novel tuning mechanism, "spectrally dependent spatial

20   filtering" refers to **spectrally dependent** beam distortion in a laser cavity where an intra-cavity **spatial filter** is present to make the round trip cavity loss a sensitive function of beam distortion and cavity alignment. In this manner, a tunable, intracavity bandpass filter is created which tunes the laser. In the zeroth order AOTF laser, the AOTF in zeroth order transmission is an SDSF tuning element, and the requirement of

25   mode matching between the return beam and the gain medium waveguide mode provides a spatial filter. Of course, other kinds of spatial filter, such as a pinhole, can also be used as part of the SDSF tuning mechanism.

Consider a laser with an intra-cavity spatial filter and an SDSF tuning element, aligned for maximum output power when the distortion is zero, (laser A). For laser A, it is clear that the introduction of any beam distortion will necessarily increase round trip cavity loss. Typically, an SDSF tuning element only distorts the beam

5   significantly over a limited range of wavelengths centered at some central wavelength λ_c. Therefore, the round trip loss will be approximately constant (and minimal) for all wavelengths that are sufficiently far from λ_c, and the round trip loss will increase as the wavelength approaches λ_c. Such a loss versus wavelength dependence will not tune the laser, since no intracavity bandpass filter is present.

10   Now consider the same laser, except that the cavity alignment differs from the alignment needed to obtain maximum output power for no distortion, (laser B). In this situation, the round trip loss versus wavelength dependence is still roughly constant for all wavelengths that are sufficiently far from λ_c, but this constant "background" loss is no longer minimal, because the loss has been increased from the background loss

15   present in laser A as a result of the cavity alignment of laser B. Thus, in the case of laser B, the SDSF tuning element can reduce the round trip cavity loss to a level that is less than the background loss, at least for some wavelengths, and furthermore the round trip cavity loss can be minimal for a wavelength λ_0 near the center wavelength λ_c. This wavelength of minimal round trip loss, at which laser emission will occur, can

20   be varied by tuning the center wavelength of the SDSF tuning element with appropriate control inputs, such as an electrical frequency or voltage. In laser B, the alignment is such that a tunable intra-cavity bandpass filter is created by the SDSF tuning element.

It is well known that the round trip loss in a laser cavity without an intra-cavity spatial filter is substantially insensitive to beam distortion and small perturbations to

25   the cavity alignment. Thus, the purpose of the intra-cavity spatial filter in the present invention is to strengthen (i.e. increase the difference between minimum loss and "background" loss for laser B) the intra-cavity bandpass filtering effect disclosed

above, by making the cavity round trip loss a more sensitive function of beam
distortion and cavity alignment. Although it is theoretically possible that adequate
laser tuning may be obtained via this mechanism in the absence of a spatial filter, it is
believed that in practice an intra-cavity spatial filter is necessary in order to obtain the

5   broad tuning range (e.g. > 30 nm) that is desirable for most applications. Detailed
discussion of the operation of this tuning mechanism is provided in connection with a
description of the drawings.

Brief Description of the Drawings

          Figure 1 shows measured single pass filtering properties of an AOTF for both

10   zeroth order and first order transmission.

          Figure 2 shows the output power, and side mode power as a zeroth order AOTF
laser is tuned over a broad wavelength range (> 70 nm). The peaks give output power,
and refer to the left vertical axis on the figure, and the circles give side mode power
and refer to the right vertical axis on the figure.

15   Figure 3 gives measured round trip cavity loss for the zeroth order AOTF laser
as the external cavity collimation lens is translated along the cavity axis, for a laser
configuration shown schematically in Figure 4.

          Figure 4 shows a schematic block diagram of an embodiment of the invention

          Figure 5 gives a typical tuning curve for a zeroth order AOTF laser with an

20   intracavity grid fixing etalon.

          Figure 6 shows the accuracy with which the open loop laser frequencies were
placed on a 50 GHz grid using a zeroth order AOTF laser with an intracavity grid
fixing etalon.

          Figure 7 shows that there is negligible hysteresis as the laser wavelength is

25   moved up, then down for a zeroth order AOTF laser with an intracavity grid fixing

etalon.

Detailed description of the drawings

Figure 1 shows measured spectra for single pass zeroth order and first order

5   transmission through an AOTF. This AOTF is a non-collinearly phase-matched

device, so there is a clear distinction between the zeroth order light path through the

device and the first order light path through the device, based on the diffraction angle

between zeroth order output and first order output. Note that the AOTF functions as a

notch filter (i.e. high transmission at all wavelengths except for a narrow wavelength

10   band centered on a tunable center wavelength λ_c) in zeroth order transmission, as seen

in Figure 1. The center wavelength λ_c of the zeroth order notch is varied by changing

the RF frequency applied to the AOTF, and the depth of the notch can be varied by

changing the RF power applied to the AOTF. Approximately 50 mW of RF power

was applied to the AOTF in this measurement. If no RF power is applied to the

15   AOTF, there is no filtering action, and the zeroth order beam is not filtered or distorted

by the AOTF.

Figure 2 shows output power and side mode power at various wavelengths

obtained from a zeroth order AOTF laser. A common measure of the spectral purity of

a laser is the side mode suppression ration (SMSR), which is the ratio of the output

20   power to the side mode power. Figure 2 demonstrates broad tunability (> 70 nm), high

spectral purity (SMSR > 40 dB in all cases, and typically SMSR > 45 dB), and good

output power uniformity across the tuning range. The zeroth order AO tuning element

in this laser functions as the SDSF tuning element as defined above, and it is

experimentally confirmed that laser tuning is only obtained when the zeroth order

25   AOTF laser cavity is misaligned from the condition of maximum output power with no

RF applied to the AOTF (i.e. no beam distortion).

Figure 3 shows measured round trip cavity loss for a zeroth order AOTF laser,

and provides clear experimental evidence for the SDSF mechanism. The results were obtained from an experiment where the drive current to the gain chip was set slightly below laser threshold. The resulting broadband amplified spontaneous emission acts as a probe to measure the intra-cavity round trip loss. The cavity configuration for this

5   experiment comprised a lens to collimate the beam emitted from the chip, plus a planar external mirror to provide feedback. The AOTF is located between the lens and the external mirror.

The cavity alignment is systematically varied by moving the lens along the cavity axis in small displacements Δz. The $\Delta z = 0$ reference point is where maximum

10   output power is obtained with no RF power applied to the AOTF. Thus, the laser with $\Delta z = 0$ is a particular case of laser A, with no intentional cavity misalignment, and lasers with $\Delta z \neq 0$ are particular cases of laser B, with intentional cavity misalignment. The 0 dB loss shown on Figure 3 is the round trip cavity loss when no power is applied to the AOTF.

15   For zero displacement, ($\Delta z = 0$), only the expected spectral notch appears in Figure 3. Note that the large loss within the notch is cut off by the vertical scale on the plot, which is chosen to best illustrate the SDSF effect. For $\Delta z \neq 0$, two effects are seen. First, the background loss increases as $|\Delta z|$ increases from 0. Second, a round trip spectral bandpass filtering behavior is observed for certain nonzero values of Δz,

20   and the height of the bandpass peak relative to the background level is a sensitive function of the misalignment Δz. This intra-cavity filter is seen to be quite strong, since the $\Delta z = -4.8\ \mu m$ case plotted in Figure 3 shows a peak height of more than 2 dB relative to the background level. An important observation to make regarding Figure 3 is that, in situations where a significant bandpass filtering behavior is observed, the

25   minimum round trip loss at the spectral peak is less than the round trip loss determined by the cavity misalignment alone (i.e. the background loss).

Thus, Figure 3 shows that the beam distortion introduced by the AOTF in

zeroth order transmission most nearly compensates for the cavity misalignment at a definite, tunable wavelength, and that the SDSF mechanism is therefore responsible for the tunability of the zeroth order AOTF laser. For the zeroth order AOTF laser, the spectrally dependent distortion is provided by the AOTF in zeroth order transmission,

5   and the spatial filter is provided by the optical waveguide present in the gain medium. That is, if a certain power P_b impinges on the waveguide endface, only some lesser amount of power P_0 is launched (i.e. coupled) into the waveguide, and the mode matching efficiency $\eta = P_0/P_b$ is a sensitive function of wavelength. We refer to loss incurred in this manner as mode matching loss.

10   Figure 4 is a schematic view of a tunable laser system 11, constructed according to one embodiment of the invention. Laser emission from a first face 15-1 of an electrically pumped semiconductor gain chip 15, which provides optical gain predominantly for TE polarization due to the use of compressively strained quantum wells in the chip active region, is collected by a ball lens 14, passes through an isolator

15   and fiber coupling lens assembly 13, and is coupled to the output optical fiber 12. The first face 15-1 of the gain chip 15 thus acts as the output coupler for this laser cavity. Inside the laser cavity 16, the beam exits from the semiconductor chip 15, with approximate horizontal and vertical beam divergences of 30 degrees and 35 degrees respectively (full angle half-maximum of intensity), at a second face 15-2, which is

20   coated and tilted to provide a reduced reflectivity endface, and passes through a collimation lens 17, having a focal length of 2.75 mm. The collimated beam is then received by a grid-fixing etalon 19(optional), whose properties and purpose are explained hereinafter. The etalon 19(optional) is present in a preferred embodiment to realize certain advantages detailed below, but is not required to implement the SDSF

25   tuning mechanism.

The beam exiting the etalon 19 is received by an AOTF 21, at a first surface 21-1, which is preferably coated with an anti-reflection (AR) coating, preferably

having a reflectivity no higher than about 0.1 percent. A suitable AOTF 21 is

CBAOTF model # F101B from Aurora Photonics, which has a specified spectral

bandwidth of ≤ 0.7 nm full width half maximum, and is typically driven by 50-100

mW of RF power. It is expected that other AO devices than CBAOTF model # F101B

5   will perform at least equivalently as a laser tuning element. Within the AOTF 21, the

laser beam propagates in the zeroth order (beam 0 in Figure 4), and a first order beam

(beam 1 in Figure 4) is generated by diffraction and propagates in a slightly different

direction. These two beams are received at spaced apart locations and angular

orientations at a second surface 21-2 of the AOTF. The surface 21-2 is preferably AR-

10   coated to reduce reflection to a negligible level (e.g., 0.1 percent).

Beams 0 and 1 are both received by a mirror/lens assembly 25, at a first surface

25-1, where this surface is coated for high reflectivity (e.g. preferably 99%). The

surface 25-1 is the mirror that defines the external laser cavity and is aligned so that

only beam 0 is retroreflected into the laser cavity 16. The angular and spatial

15   separation of beam 0 and beam 1 is sufficient to ensure beam 1 is not retroreflected

into the laser cavity 16. The laser cavity 16 includes all elements between the surface

15-1 of the gain chip 15 and the surface 25-1 inclusive.

The surface 25-1 has a specified level of transmission (e.g. approximately 1

percent), so that a known small fraction of various intracavity optical beams passes

20   through surface 25-1 to be received by diagnostic elements (elements 27 through 33

inclusive). There are three beams of interest for the diagnostics. The first two of these

three beams are beams 0 and 1, the zeroth order and first order beams respectively. A

third beam, called "beam E", is the beam (dotted line on Figure 4) that is generated by

reflection of the circulating laser beam from the etalon 19. The etalon 19 is tilted with

25   respect to the cavity axis, so beam E propagates in a different direction from beam 0,

as indicated, and is not retroreflected back into the laser cavity 16 by the mirror 25-1.

Beams 0, 1 and E are received by a second surface 25-2, of the mirror/lens

assembly 25, which is coated for low reflectivity (e.g. ≤ 0.1 percent), and is curved to provide the appropriate focusing power into diagnostic elements 27-33 inclusive. Beams 0, 1 and E are then received by a beam splitter 27, which directs roughly half the power in each of the three beams toward a first detector array 31 (beams 0a, 1a and

5   Ea) and toward a second detector array 33 (beams 0b, 1b and Eb).

Beams 0a and Ea are received by two detector elements, e.g. 31A and 31B respectively, in the detector array 31. In addition, beam 1a misses all the elements of detector array 31, as indicated. Beams 0b, 1b and 2b are received by a linear transmission filter (LTF) 32. The LTF attenuates each beam by a factor that is a linear

10   function of wavelength. Beams 0b and 1b, upon transmission through LTF 32, are received by two detector elements, e.g. 33A and 33B respectively, of detector array 33. In addition, beam Eb misses all elements of detector array 33, as indicated.

With this arrangement, three control signals are obtained. The first control signal is the ratio of beam 0b at 33A to beam 0a at 31A. This ratio provides a direct

15   measure of the emission wavelength of the laser, because the LTF 32 is in the optical path leading to detector array 33. The second control signal is the ratio of beam 1b at 33B to beam 0b at 33A of detector array 33. This ratio is a sensitive function of the location of the laser wavelength with respect to the zeroth order spectral notch of the AOTF, and can be used as an input to an appropriate control loop to keep the AOTF

20   tuning element from drifting with respect to the lasing mode. This second control signal is not affected by the presence of the LTF 32 in the optical path leading to detector array 33, since the LTF attenuates beams 0b and 1b by the same factor. The third control signal is the ratio of beam Ea at 31B to beam 0a at 31A of detector array 31, which is a measure of how well the lasing mode is aligned to the etalon. An

25   appropriate control loop can use this control signal to ensure mode-hop-free operation by locking the lasing mode to the etalon.

Operation of the zeroth order AOTF laser depends on the manner in which the

cavity is aligned. Although the indicated procedure below might need to be modified if the components that comprise the laser system change, those skilled in the art will be able to readily carry out appropriate alignment procedures. The alignment procedure that was used in Figure 4 comprised the following steps:

5   1) Align laser for maximum output power with only chip, lens and back mirror in place (i.e. elements 15, 17 and 25-1 respectively in figure 4).

2) Insert AOTF (element 21 in figure 4) into cavity with no RF power applied to the AOTF. The AOTF is a noncollinearly phase matched device, and is inserted such that the relevant optical and acoustic wave vectors all lie in the X-Z plane of

10   Figure 4. Adjust the AOTF so that the beam hits the back mirror at the same vertical (i.e. Y direction on Figure 4) height as before.

3) Translate back mirror horizontally (i.e. X direction on Figure 4) to center mirror on the beam. This step is necessary due to a roughly 3 mm beam walkoff due to the birefringence of the TeO_2 crystal used in this AOTF. The laser output power does

15   not change appreciably when steps 2 and 3 are performed.

4) Apply RF power to the AOTF and choose an RF frequency such that the zeroth order AOTF filter notch is on the blue (i.e. shorter wavelength) side of the observed spectral peak of the broadband laser emission.

5) Translate the lens 17 along the cavity axis (i.e. Z direction on Figure 4),

20   and/or change tilt of back mirror 25-1, until a transition from broadband lasing emission far from the AOTF notch to single mode lasing emission at an edge of the AOTF notch is observed.

6) Systematically and sequentially adjust lens 17 position (X, Y and Z), mirror 25-1 tilt (towards X and Y) and AOTF 21 position (X and Y) to maximize wavelength

25   range in which single-mode tunable lasing is observed. Such systematic adjustment procedures are well know to those skilled in the art.

7) Insert grid fixing etalon 19 and repeat step 6.

The function of the grid fixing etalon 19 in figure 4 can be appreciated by considering Figures 5, 6 and 7, which all pertain to a zeroth order AOTF laser with a grid fixing etalon inserted within the cavity.   Figure 5 gives a typical tuning curve,

5   where the presence of the grid fixing etalon causes the laser to tune in discrete steps as the RF frequency applied to the AOTF is swept. The reason for this is that the etalon introduces a high intracavity loss at all wavelengths except at its transmission peaks. Therefore, the laser can lase only at or very near an etalon transmission peak, and the spacing between the wavelength steps is determined by the etalon free spectral range,

10   e.g. 50 GHz. Figure 6 shows that excellent open loop wavelength accuracy is obtained in practice, where the deviations from an exact 50 GHz grid are less than 1 GHz over a total range of 100 channels (i.e. 5 THz). Figure 7 shows a small portion of the tuning curve, where the RF frequency is first swept up, then swept down. Hysteresis in the tuning curve is seen to be essentially negligible.

15   The presence of a grid fixing etalon within a tunable laser, such as the zeroth order AOTF laser, provides nonobvious advantages for applications where the laser is required to tune to channels that lie on a fixed, evenly spaced, frequency grid. The dense wavelength division multiplexing (DWDM) application is a primary example of such an application, where the ITU grid is the relevant fixed frequency grid. In some

20   DWDM applications, such as sources for test equipment, the open loop wavelength accuracy provided by the grid fixing etalon can provide the required accuracy. In these cases, the use of a grid fixing etalon allows the wavelength control loop that is typically necessary in such sources to be eliminated, which is clearly advantageous. For other DWDM applications, such as sources for optical communication, the use of a

25   grid fixing etalon may not permit elimination of the wavelength control loop. In such cases, the presence of a grid fixing etalon still provides advantages, such as reduced total size and part count (relative to a laser + external locker configuration), and greater

flexibility in overall laser control, since wavelength accuracy is ensured with a stable, passive intracavity device.

In order to perform its intended function, the grid fixing etalon 19 in Figure 4 is preferably inserted into the laser cavity 16 such that the etalon surface normals make a

5   small angle (preferably 1-10 degrees) with respect to the cavity axis, to thereby ensure that the beams reflected from the etalon surfaces do not efficiently couple into the laser cavity. The etalon finesse is moderate (e.g. 2 < finesse < 10), and this value of finesse is chosen to provide low loss in transmission through the tilted etalon, and the desired level of spectral selectivity. Since the etalon serves as an absolute wavelength

10   reference for the laser, the etalon is preferably fabricated using materials, such as fused silica, that are mechanically stable and temperature insensitive.

Note that, as previously indicated, implementation of the basic SDSF tuning mechanism does not require the use of a grid fixing etalon. The embodiment of a laser based on the SDSF tuning mechanism, i.e. the zeroth order AOTF laser which has been

15   described in detail, has a grid fixing etalon inserted into the cavity to realize the indicated additional advantages that are over and above those of the laser tuning mechanism.

Many of the advantages that are provided by insertion of a grid fixing etalon within a tunable laser can be achieved using similar methods, such as by appropriately

20   engineering a parasitic etalon that is already present within the cavity (e.g. an etalon formed by the two faces of a semiconductor gain chip) to perform the grid fixing function. It is also possible to use the overall optical path length of the laser cavity to perform the grid fixing function, since the longitudinal mode spacing of a laser is determined by the round trip optical path length. In general, we refer to such lasers as

25   featuring "discrete tunability".

As is evident from the preceding description, the present invention provides a novel laser and laser tuning mechanism, of which a preferred embodiment is the zeroth

order AOTF laser. As such, it will be apparent to one skilled in the art that various

modifications to the details of construction and method shown here may be made

without departing from the scope of the invention, e.g. folding the optical path within

the laser cavity and/or tuning element in order to make the laser more compact. The

5   application of well known laser engineering principles to lasers which tune via the

disclosed mechanism fall within the scope of the present invention, since such

application would constitute an obvious combination of engineering prior art with the

novel laser tuning mechanism herein disclosed.

It will also be apparent to those skilled in the art that the operating principles

10   that govern the selection of a single oscillation frequency for the tunable laser can also

be employed to obtain non-tunable single frequency operation of a laser. For example,

a static volume hologram in zeroth order transmission is a suitable wavelength

determining element for this application.